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Citation: Moawwad, Ahmed, Vinod Khadkikar, and James L. Kirtley. Photovoltaic Power Plant as FACTS Devices in Multi-feeder Systems. In IECON 2011 - 37th Annual Conference of the IEEE Industrial Electronics Society, 918-923. Institute of Electrical and Electronics Engineers, 2011.

As Published: <http://dx.doi.org/10.1109/IECON.2011.6119433>

Publisher: Institute of Electrical and Electronics Engineers (IEEE)

Persistent URL: <http://hdl.handle.net/1721.1/79670>

Version: Author's final manuscript: final author's manuscript post peer review, without publisher's formatting or copy editing

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Photovoltaic Power Plant as FACTS Devices in Multi-Feeder Systems

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Abstract—This paper illustrates possible configurations for a large-scale photovoltaic power plant (PV), to operate as a FACTS (flexible AC transmission system) device in addition to operating as a source of renewable power generation. The inverters in PV plant are reconfigured in such a way that two or more distribution networks/feeders are interconnected. This newly developed system where inverter modules are connected in back to back is addressed as Interline-PV (I-PV) system. Based on the inverter reconfiguration, three distinct topologies can be realized, namely, (i) Shunt I-PV, (ii) Series I-PV and (iii) Shunt-Series I-PV. These configurations enable the PV power plant to operate through two adjacent power system networks/feeders.

The proposed configurations of PV system can act as Inter Line Power Flow controller (IPFC), Static Synchronous Compensator (STATCOM), or Unified Power Flow Controller (UPFC). The new configurations expand the role of PV plant to regulate the network/feeder voltages, support active and reactive powers and enhance the overall dynamic performance of both the feeders. This paper discusses the advantages and limitations of each of the I-PV systems. A simulation study is done to illustrate some of the benefits offered by I-PV systems.

Index Terms—Flexible AC transmission system (FACTS), interline power system, active and reactive power control, voltage regulation, photovoltaic power generation and control, power management.

I. INTRODUCTION

Renewable energy resources are being considered as one of the best solutions to resolve the ever increasing electricity demand worldwide. In this context, photovoltaic (PV) and wind turbine power plants can generate power of as much as hundreds of MWs. The reliability impact of these resources is an important aspect that needs to be assessed because their large scale of penetration may affect the proper operation of the power system distribution networks [1-5]. These plants inject active power into the network, and so they may cause fluctuations in the power injected as they depend mainly on

fluctuating natural resources or they may cause voltage variations [6-10].

Interconnecting power systems together improves the compatibility of the whole power system. By doing so, the control of active and reactive power flow through these interconnected systems can help to improve the performance of the whole network/feeder. Flexible AC transmission system (FACTS) devices have the capability to increase the power transfer limit of transmission lines. Some of the commonly used FACTS devices are: Static synchronous series compensator (SSSC), static synchronous compensator (STATCOM), interline power flow controller (IPFC), unified power flow controller (UPFC) and thyristor controlled series compensator (TCSC) [10-13].

Some recent research developments suggest the possible utilization of PV plant inverters to do tasks in addition to converting DC power into AC, such as supporting the line/feeder voltage, reactive power compensation and harmonic filtering [9-14]. In context with multifunctional utilization of a PV solar plant inverter, this paper proposes and compares between three new system configurations for the PV power plants. These new configurations enable PV power plants to work as FACTS devices.

Three new configurations of large PV power plants could integrate to more than one distribution network/feeder. The idea is to connect PV power plant inverters to two different adjacent distribution networks. The proposed configurations are called as Inter-line PV (I-PV), and are classified as:

- i) Shunt I-PV: two distribution networks are connected to each other by reconfiguring the PV inverters, connecting a few modules back-to-back, such that the inverter modules are shunt connected with both the feeders [15].
- ii) Series I-PV: in this configuration the back to back inverter modules are connected in series with both feeders. This configuration closely resembles the Interline Power Flow Controller (IPFC) system.
- iii) Series-Shunt I-PV: in this configuration one of the back to back inverters is connected in shunt with one feeder while the other inverter is connected in the series with second feeder thus achieving a system similar to the UPFC structure.

The above configurations can be used to regulate the feeder voltages, compensate for both active and reactive powers, independently for each of the feeders besides injecting active power from the PV arrays. These configurations can be used during day as well as night time. A MATLAB/SIMULINK based study is carried out to illustrate the effectiveness of some of the I-PV systems.

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This work is supported by Masdar Institute under MIT-Masdar Institute joint research project grant.

II. PROPOSED CONFIGURATIONS FOR PV SYSTEM

Fig.1 shows a two feeder distribution system. Feeder-I and Feeder-II are considered to be located close to each other. A large-scale PV plant is assumed to be connected on one of the feeders (in this case, Feeder-1). The large-scale PV power plant, in the order of few MWs, is realized by installing an approximate number of the relatively smaller rating (500 kW to 1 MW) inverter modules. These inverter modules can be seen as small PV solar power generation units within a large-scale PV solar plant.

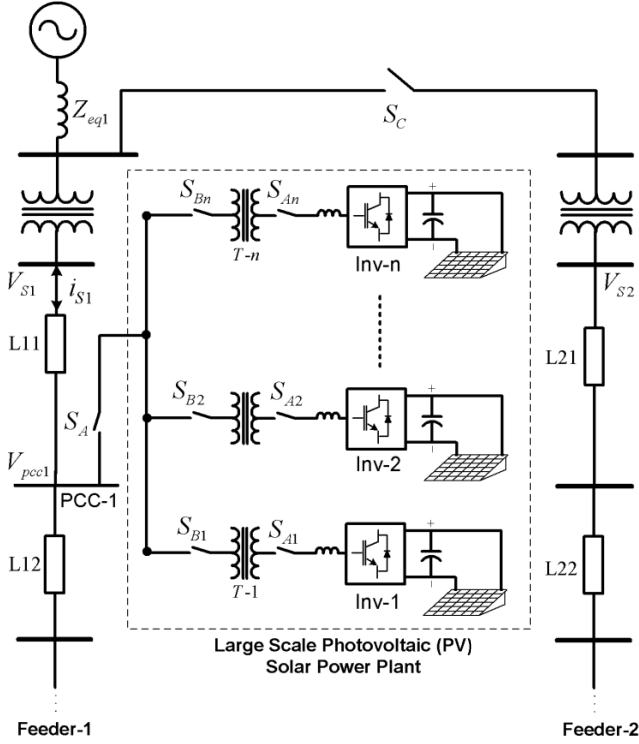


Fig. 1 Regular large-scale PV solar power plant configuration.

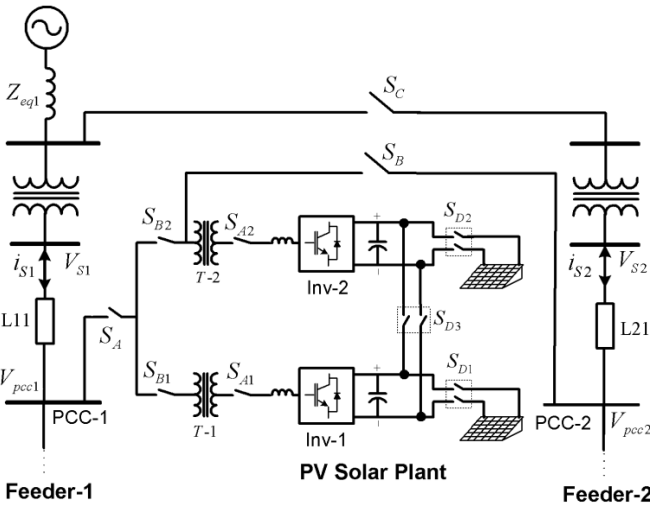


Fig. 2 Proposed Shunt I-PV system configuration.

In Fig.2 the PV solar plant inverters are reconfigured in such a way that two feeders can be interconnected with each other.

Since both the inverters are connected across the feeder-1 and feeder-2, it is named as shunt I-PV system. For demonstration, only two PV power plant inverters are considered in this study. For a large-scale PV plant there will be additional similar units each representing I-PV system unit. S_A and S_B are considered as the main switches that are used to connect PV power plant to networks (feeder-1 and feeder-2, respectively). The two inverters can be connected back to back on the DC side through switch S_{D3} . Switches S_{D3} and S_B are newly added component to realize the proposed system configuration. For normal PV power plant operation, switches S_A , S_{B1} , S_{A1} , S_{D1} , S_{B2} , S_{A2} and S_{D2} are all closed to connect the PV plant to feeder-1, while the switches S_{D3} and S_B are opened. The proposed system configuration requires following additional features to be added:

- DC bus network at the DC side of the solar system to form a common DC link between the inverters and the switch S_{D3} .
- Connecting lines between the inverter units and adjacent feeders and switch S_B .

To operate the PV plant as I-PV system, switches S_A , S_{B1} , S_{A1} , S_{D1} , S_{A2} , S_B , S_{D2} and S_{D3} are closed, while switch S_{B2} is kept open. During night-time when PV solar plant does not produce real power, the switch S_{D1} and S_{D2} can be opened. We should notice here that transformer-1 and transformer-2 are rated approximately to the same ratings of the two inverter units. Some of the functionalities that could be accomplished using shunt I-PV system configuration are listed below:

- Provides the PV solar plant generated active power to feeder-1 or feeder-2 or partly to feeder-1 and feeder-2.
- Real power management between feeder-1 and feeder-2 through PV solar power inverters. In such cases, one inverter unit will act as controlled rectifier drawing the power from one feeder while the second inverter unit delivers this power to other feeder.
- Provides appropriate shunt reactive power compensation to increase the steady state transmittable power.
- Regulates the feeder voltages at the point of common coupling.
- Increases transient stability limit and may provide effective power oscillation damping.
- Expands the usage of PV power plants especially the large ones to utilize them during nighttime hours as an independent FACTS devices to enhance the overall power system performance.

Fig. 3 (a) shows another possible system configuration in which the inverter modules are connected in series with line, called as series I-PV system. To realize this configuration the PV solar plant transformer needs to be placed in the series with main line, thus requires additional switches as shown in the Fig. 3 (a). The series I-PV configuration could be realized by closing switches S_{A1} , S_{B1} , S_2 , S_B , S_{B2} and S_4 , while keeping switches S_1 , S_3 , \bar{S}_2 and \bar{S}_4 open. It is important here to mention that shunt compensation is ineffective in controlling the actual transmitted power, which at a defined transmission voltage is determined by the series line impedance and the angle between the end voltages of the line, thus series compensation is very important to imitate the role of variable line impedance.

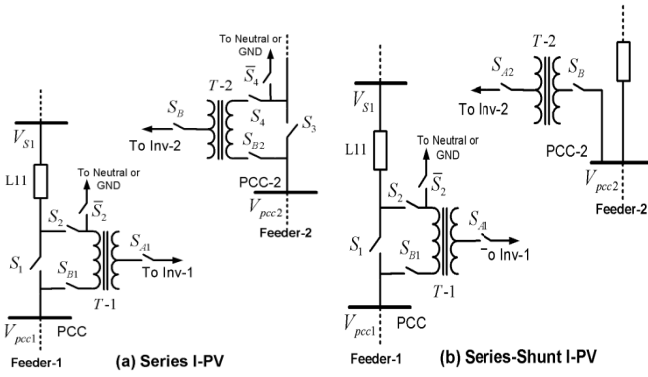


Fig. 3. Proposed I-PV system configurations: (a) Series I-PV system (b) Series-shunt I-PV system.

Some of the key features of series I-PV system are:

- Increased maximum power transferable through feeder by injecting series voltage.
- Increased transient stability limit much more effectively than with shunt compensation.
- Limited active and reactive power injection due to the limitation on the series injected voltage to maintain the resultant feeder voltage within the standard limits.
- Requirement of significantly high rating series transformer may impose additional limitations.

Fig. 3 (b) shows the arrangement for the third PV system configuration, in which one inverter module is connected in the series with one feeder, whereas, the second inverter unit in shunt with other feeder. The configuration thus achieved is similar to the unified power flow control (UPFC). This configuration could be realized by closing switches S_{B1} , S_2 , S_{A1} , S_{A2} and S_B , while opening switches S_1 and \bar{S}_2 . In this case, feeder-1 is series connected and feeder-2 is shunt connected. The configuration can also be realized in vice-versa where feeder-1 can be connected in shunt while feeder-2 in the series. Nevertheless, it combines advantages of both shunt and series compensation and could provide a better control over both active and reactive power flow.

The following points summarize the general ideas for the above three configurations:

- Shunt I-PV: can inject bulk of active power into one power system network or multiple adjacent networks. It can produce reactive power as well (if permissible), and circulate the active power between the networks. This configuration doesn't need require large number of additional devices (such as, circuit breakers) to reconfigure the PV power plant system.
- Series I-PV: can inject small amount of active power into the network due to the small injected voltage limit, but it may increase the power transferred of the network significantly. More numbers of additional devices are required to reconfigure this configuration. Furthermore, this configuration needs high capacity transformer in series with the network.
- Series Shunt I-PV: combines the advantages of both series and shunt compensation and it could provide better power flow control for the adjacent networks. The issues of

connecting a large rated series transformer is also present in this configuration.

III. SIMULATION STUDY

In this section, a simulation study based on the proposed shunt I-PV and series I-PV systems is discussed to illustrate the feasibility of realizing such a system configurations and their effectiveness in improving the overall power system performance.

A. Systems under consideration

A power distribution network resembling the two feeder network configuration and a PV solar plant of Fig. 1 is considered. The voltages of the two feeders are considered as 11 kV. The loads on the feeders are normalized as PQ loads, located at the ends of each feeder. The loads have different values on each feeder. The voltages V_{pcc1} and V_{pcc2} represent the voltages at the point of common coupling at feeder-1 and feeder-2, respectively. P_{inv1} & Q_{inv1} and P_{inv2} & Q_{inv2} are the active and reactive powers injected or absorbed by Inv-1 and Inv-2, respectively. The leading reactive powers supported by Inv-1 and Inv-2 are shown as positive quantities, while the lagging reactive powers are shown as negative quantities. The simulation results are expressed in per unit (*pu*), with base voltage of 11 kV and base MVA of 1. Appendix-I contains the detailed data for the system under simulation.

B. Control design for the shunt PV system

In this section the control algorithm for the shunt I-PV system is briefly described. A similar controller is realized for the series I-PV system. The inverters in both configurations are controlled to deliver both active and reactive power. Furthermore, each individual inverter module, such as Inv-1 and Inv-2, is controlled independently.

Fig. 4 shows the control diagram for Inv-1. It is controlled to inject active power into the grid and to regulate the PCC voltage simultaneously. A phase locked loop (PLL) maintains the synchronization with feeder-1. The reference injected active power is controlled through PI controller. Similarly, additional PI controller loop is used to regulate the PCC voltage.

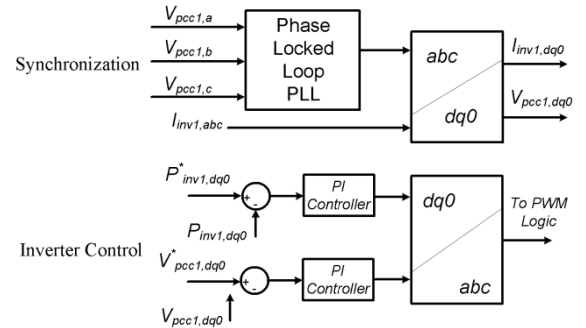


Fig. 4 Controller diagram for Inv-1.

The control diagram for Inv-2 is illustrated in Fig. 5. It is considered that the Inv-2 would support the load reactive power requirement on the feeder-2 locally. In this case the Inv-2 can provide the active power generated by PV plant and the load reactive power demand simultaneously.

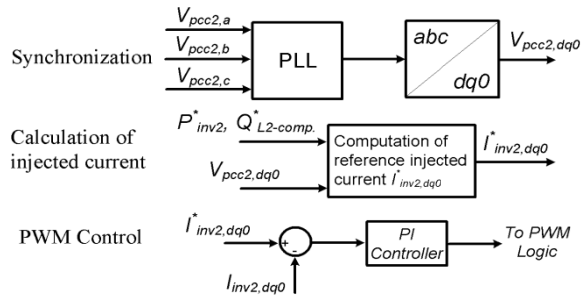


Fig. 5 Controller diagram for Inv-2.

C. Simulation Results

The simulation results are provided in Fig.6 through Fig.11.

(i) Shunt I-PV System Performance

Fig. 6 shows the performance of feeder-1 with the proposed shunt I-PV system configuration. Following are the important simulation timelines:

- t_{a1} : Inv-1 injects 1 MW active power generated form PV plant into feeder-1.
- t_{b1} : the 1 MW generated power is shared between feeder-1 and feeder-2, 0.5 MW is delivered to each feeder
- t_{c1} : Inv-1 regulates the feeder-1 PCC voltage at 1 pu through reactive power control.

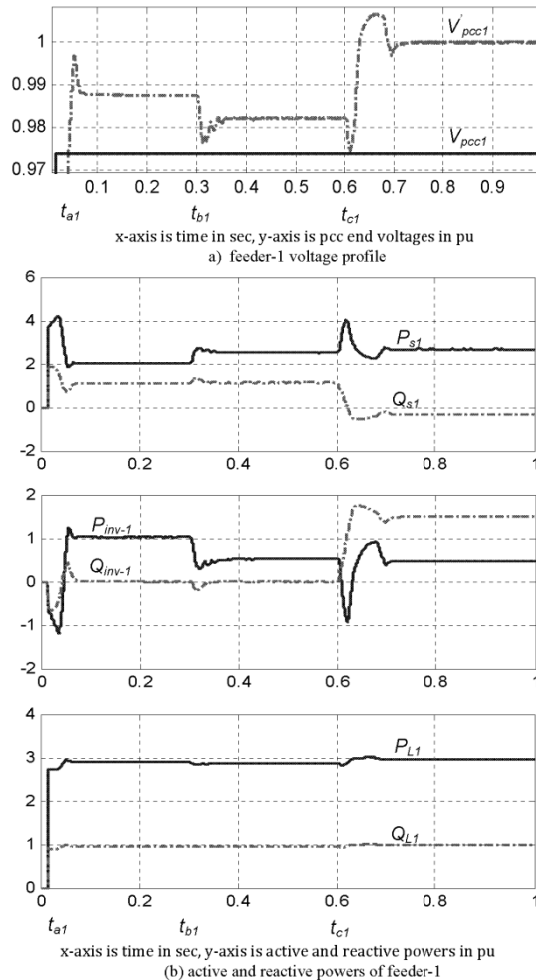


Fig.6. Feeder-1 performance with shunt I-PV system

Fig. 6 (a) shows the voltage profile of the PCC voltage before and after the regulation. V_{pcc1} and V_{pcc2} represent the voltages after and before regulation respectively. When 1 MW active power is injected into feeder-1, its PCC voltage is noticed as 0.988 pu. At time t_{b1} , when only 0.5 MW active power is injected into feeder-1 (due to equally active power sharing between feeder-1 and -2) the PCC voltage is changed to 0.982 pu. In order to regulate the PCC voltage at 1 pu, at time t_{c1} , the Inv-1 is controlled to support the necessary reactive power. The improved PCC voltage profile at 1 pu, after time t_{c1} , can be noticed from the Fig. 6 (a). The corresponding active and reactive powers at sending end (denoted by subscript “s1”), Inv-1 terminal (denoted by subscript “inv1”) and load end (denoted by subscript “L1”) are given in Fig. 6 (b).

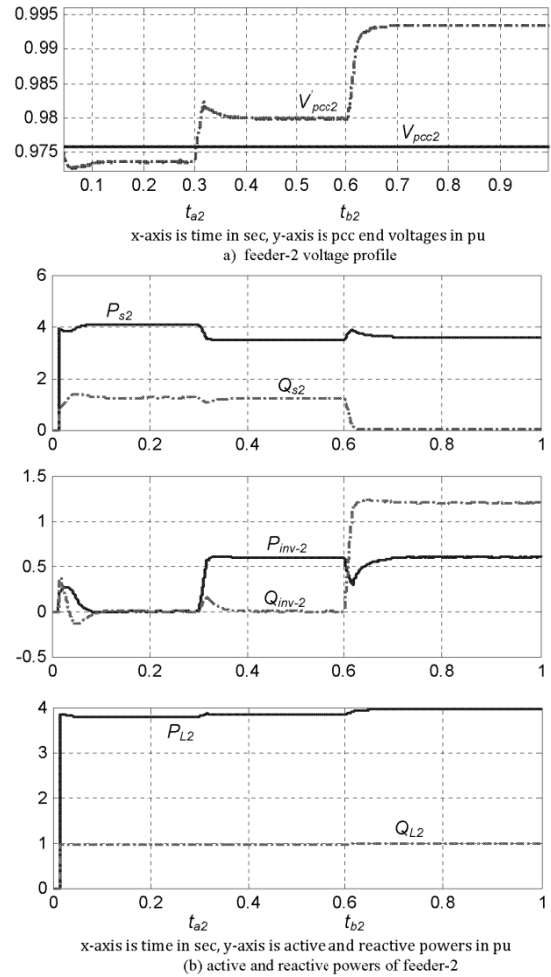


Fig.7 feeder-2 performance with shunt I-PV system

Fig.7 shows the performance of feeder-2 with the proposed shunt I-PV system configuration. Following are some important times for the simulation part:

- t_{a2} : Inv-2 injects 0.5 MW active power into feeder-2. 1 MW power generated by PV system is equally shared by inverter-1 and -2.
- t_{b2} : Inv-2 compensates the load reactive power, in this case 1 MVAR.

Fig.7 (a) shows the PCC voltage profile before (V_{pcc2}) and after (V_{pcc1}) compensation. After time t_{a2} , a slight increase in PCC voltage, from 0.975 to 0.98 pu, can be noticed. This is due the injection of 0.5 MW active power. At time t_{b2} , the inverter starts compensating the load reactive power demand. Hence, the sending end reactive power (Q_{s2}) is reduced, as noticed from the Fig.7 (b) and the PCC voltage changed to 0.9948 pu.

A constant DC-link between Inv-1 and Inv-2 is important to achieve adequate inverter functions. Fig. 8 shows the capacitor DC voltage on the link between the two inverters. This DC voltage is kept constant through appropriate control of Inv-2. As illustrated in Figs. 6 and 7, the proposed shunt I-PV system can help to achieve several control objectives. Some of the aspects highlighted here are, PV generated active power management between feeder-1 and -2, voltage regulation on feeder-1, load reactive power compensation on feeder-2. Thus, the proposed I-PV system configuration could be very useful to achieve improved overall power system performance.

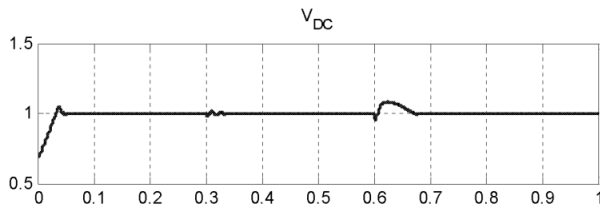


Fig.8 DC link voltage between the inverters

(ii) Series I-PV System Performance

The simulation results when the PV solar plant is configured as series I-PV system are discussed in the Figs 9-10. As PV solar plant inverters are connected in series with the feeder-1 and -2, this configuration could be more attractive during nighttime when solar plant does not produce any real power. Fig.9 shows the performance of feeder-1 with the proposed series I-PV system configuration. Following are important simulation timelines:

- t_{a1} : Inv-1 regulates the PCC voltage on feeder-1.
- t_{b1} : Inv-1 absorbs some active power from feeder-1 to circulate it through feeder-2 through Inv-2.

Fig. 9 (a) shows the PCC voltage profile before (V_{pcc1}) and after (V_{pcc2}) compensation. Inv-1 starts the operation at time = 0.6 sec to regulate the PCC voltage around 1 pu. Fig. 9 (b) shows corresponding active and reactive powers at sending end, Inv-1 terminal and at the load end. At time t_{b1} , the Inv-1 absorbs 0.1 pu active power from feeder-1. This real power is then delivered to feeder-2, shown in Fig. 10 (b).

Fig.11 shows the performance of feeder-2 with the series I-PV system configuration. Following are the simulation timelines:

- t_{a2} : Inv-2 compensates for some percentage of load reactive demand on the feeder-2.
- t_{b2} : Inv2 delivers the active power from the feeder-1 to feeder-2.

The above mentioned operations are similar to the IPFC, where one can circulate active power between two or more power systems and control the reactive power independently.

To achieve this operation, the DC link between the two inverters is maintained constant, shown in Fig.11.

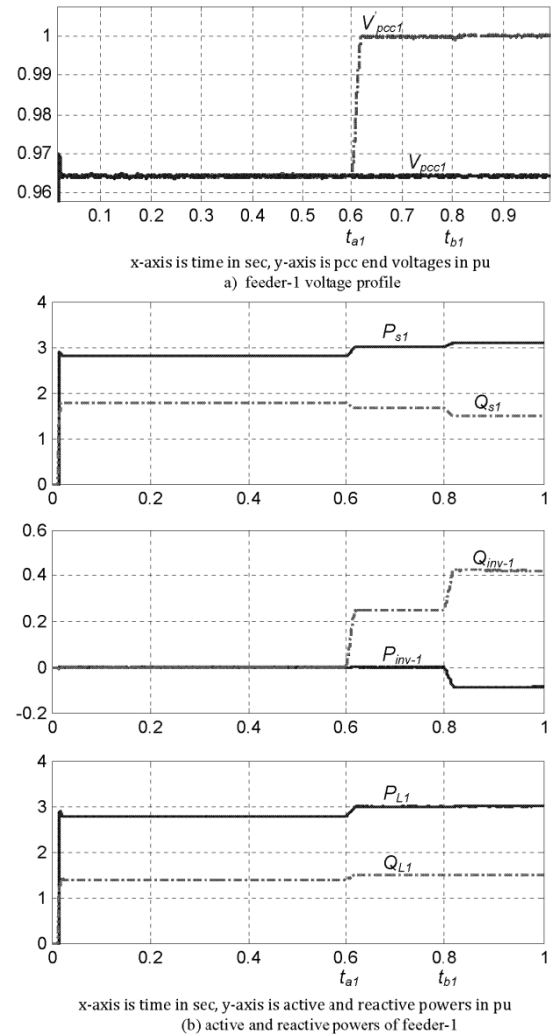


Fig.9 feeder-1 performance with series I-PV system

Following important observation can be made by studying the shunt and series I-PV system performance discussed in the Figs. 6 to 11:

- Both the configurations show capability to exchange real power between the two feeders. Though, shunt I-PV system appears more promising as this configuration does not significantly modify the original PV power plant system.
- The series I-PV system is more attractive to regulate the PCC voltage compare to shunt I-PV system due to very small amount of reactive power requirement. Though the rating of the series transformer could be significantly high and may impose limitation in realizing such a system.
- To support the load reactive power locally through I-PV systems, the shunt I-PV system could be more appropriate over series I-PV system. A small injection of reactive power through series I-PV system improves the PCC voltage significantly and therefore, it imposes limitation on amount of reactive power that can be injected from the series I-PV system.

Nevertheless, the simulation study shows that the proposed I-PV system configurations can be useful to improve the overall power system performance (such as, reactive power support, voltage regulation and real power flow control) using PV solar power plant and with some modification may help to interconnect two or more distribution networks.

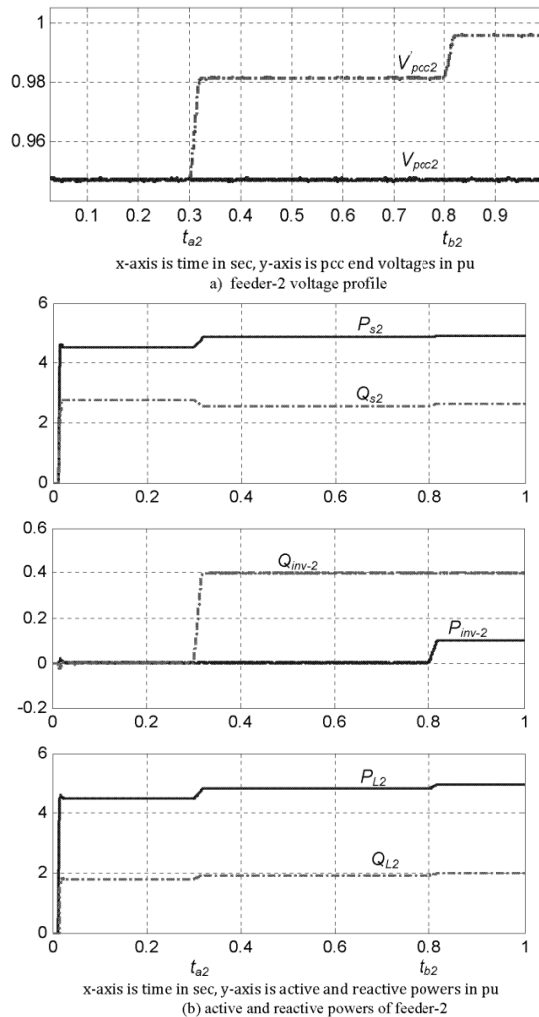


Fig.10 feeder-2 performance with series I-PV system

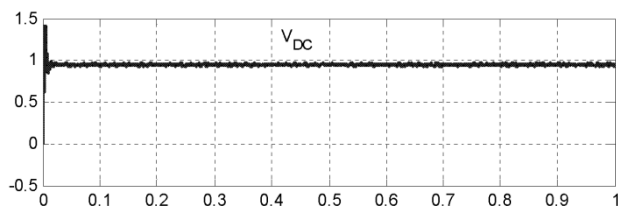


Fig.11 DC-link between the inverters

IV. CONCLUSION

In this paper, it is shown that a PV solar plant can be reconfigured as three FACTS devices in a multi-feeder system. The concept is called the Interline PV (I-PV) system and the developed configurations are: (i) shunt I-PV, (ii) series I-PV and (iii) shunt-series I-PV. All the studied configurations have capability to exchange real power between two feeders

using PV solar plant inverters. However, the shunt I-PV system found more promising since this configuration does not significantly modify the original PV power plant system. The series I-PV system could be more useful to regulate the PCC voltage and control power flow on both the feeders. The required rating of series transformer for series I-PV and series-shunt I-PV could be significantly high and may impose limitation in realizing such systems. Nevertheless, these configurations enable us to expand the use of large-scale PV power plants to compensate for active and reactive powers, regulate the feeder voltages, and management of real power flow between interconnected feeders, and so forth.

V. APPENDIX-I

Feeders-1 and -2 system voltage level, $V_{s1} = V_{s2} = 11$ KV.

Line parameters: $0.2 + j0.23$ ohm/Km.

Line lengths: $L_{11} = L_{21} = 10$ Km, $L_{12} = L_{22} = 2$ Km

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